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125 GEV HIGGS BOSON, ENHANCED DI-PHOTON RATE, AND GAUGED U(1)$_{PQ}$-EXTENDED MSSM

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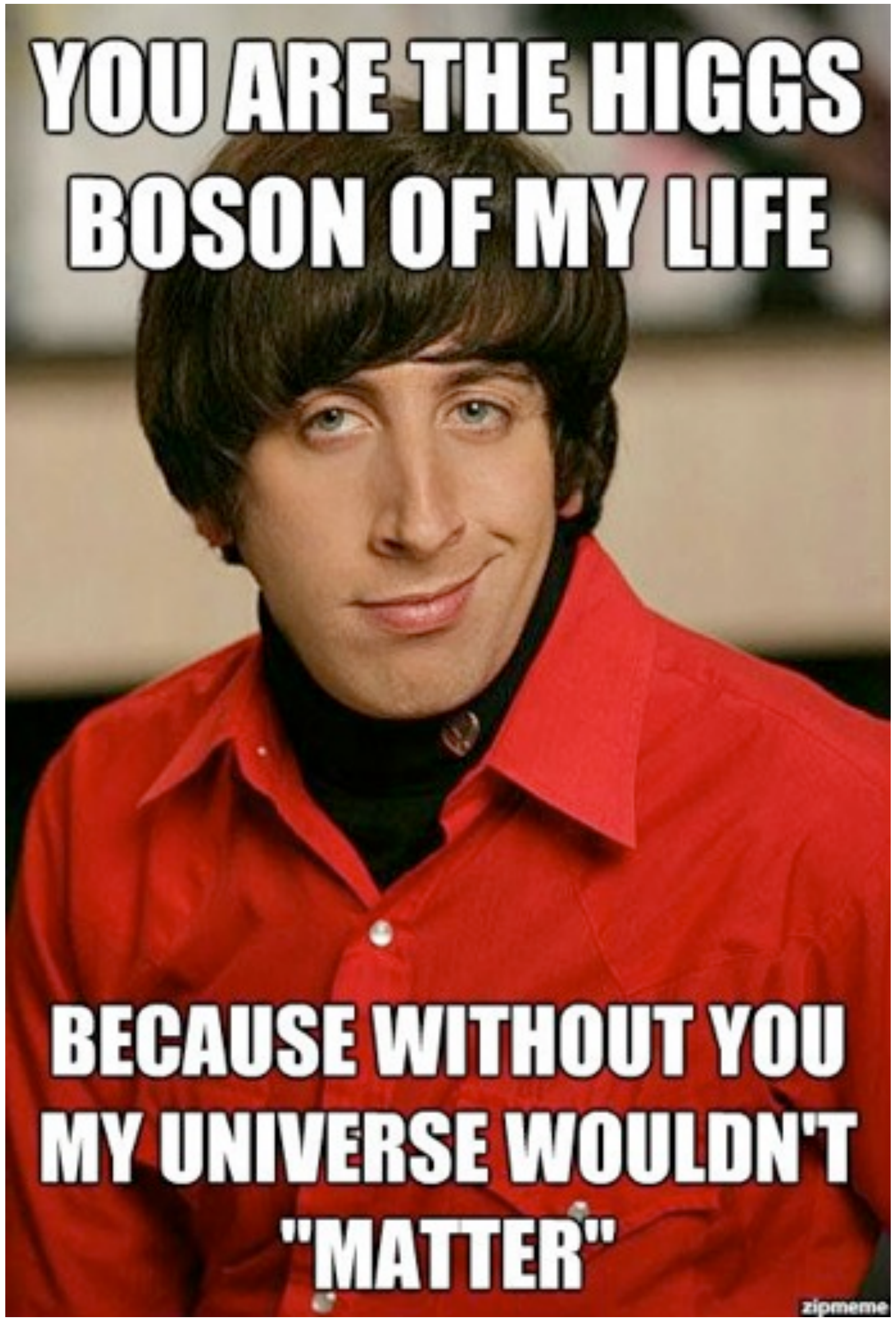
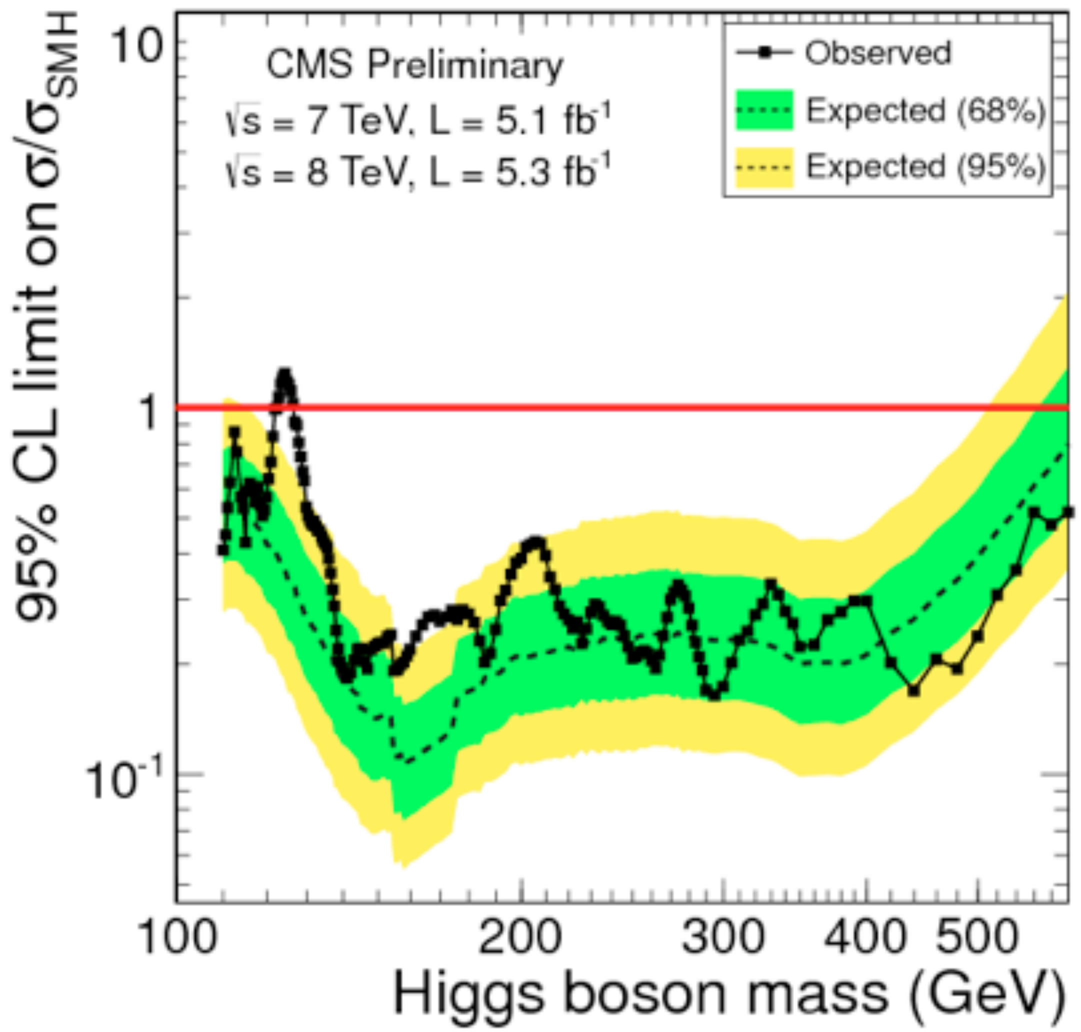
Based on Arxiv:1207.2473., in collaboration with H.P. An and L.T. Wang

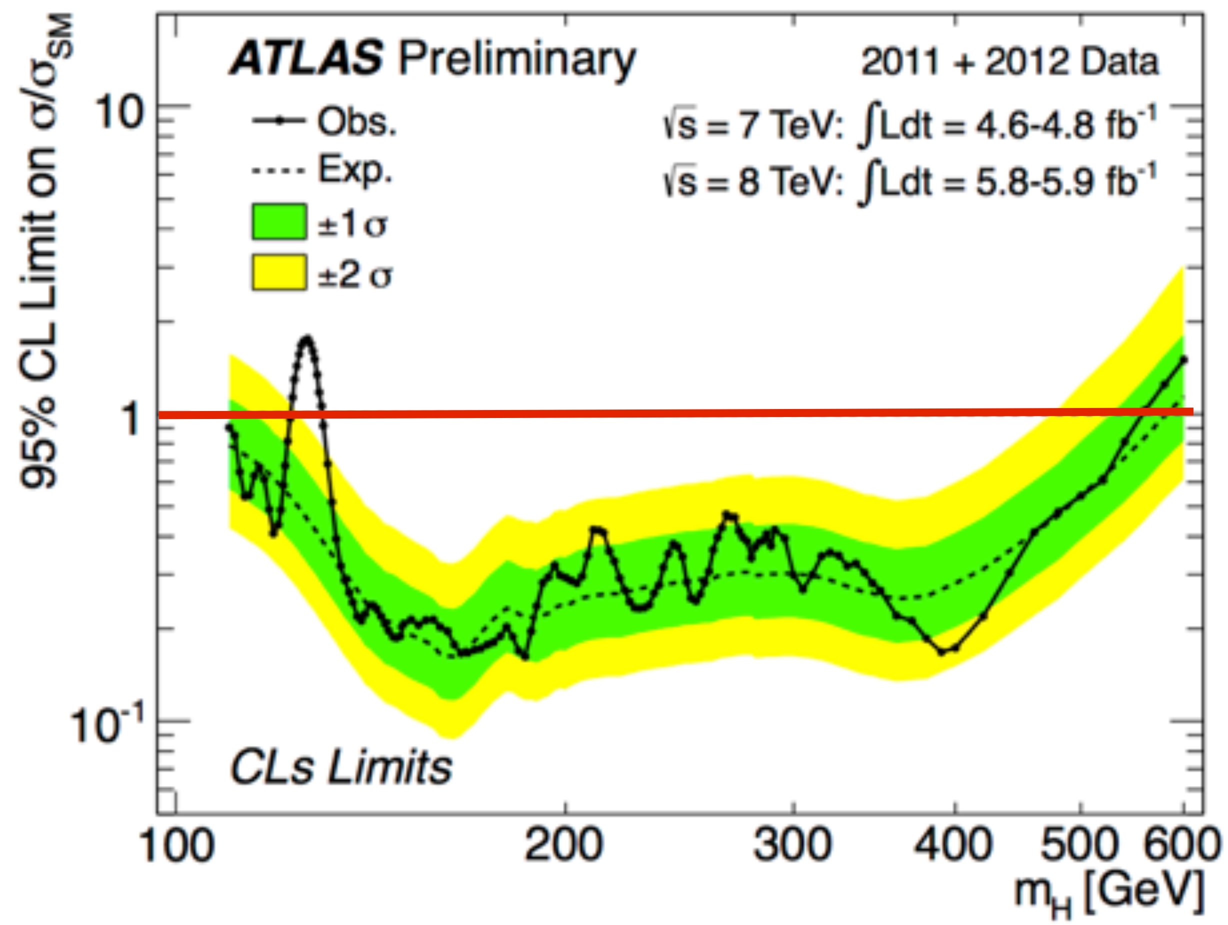
Why Higgs Boson ?



Progress at the LHC

[Atlas+CMS, 2012]

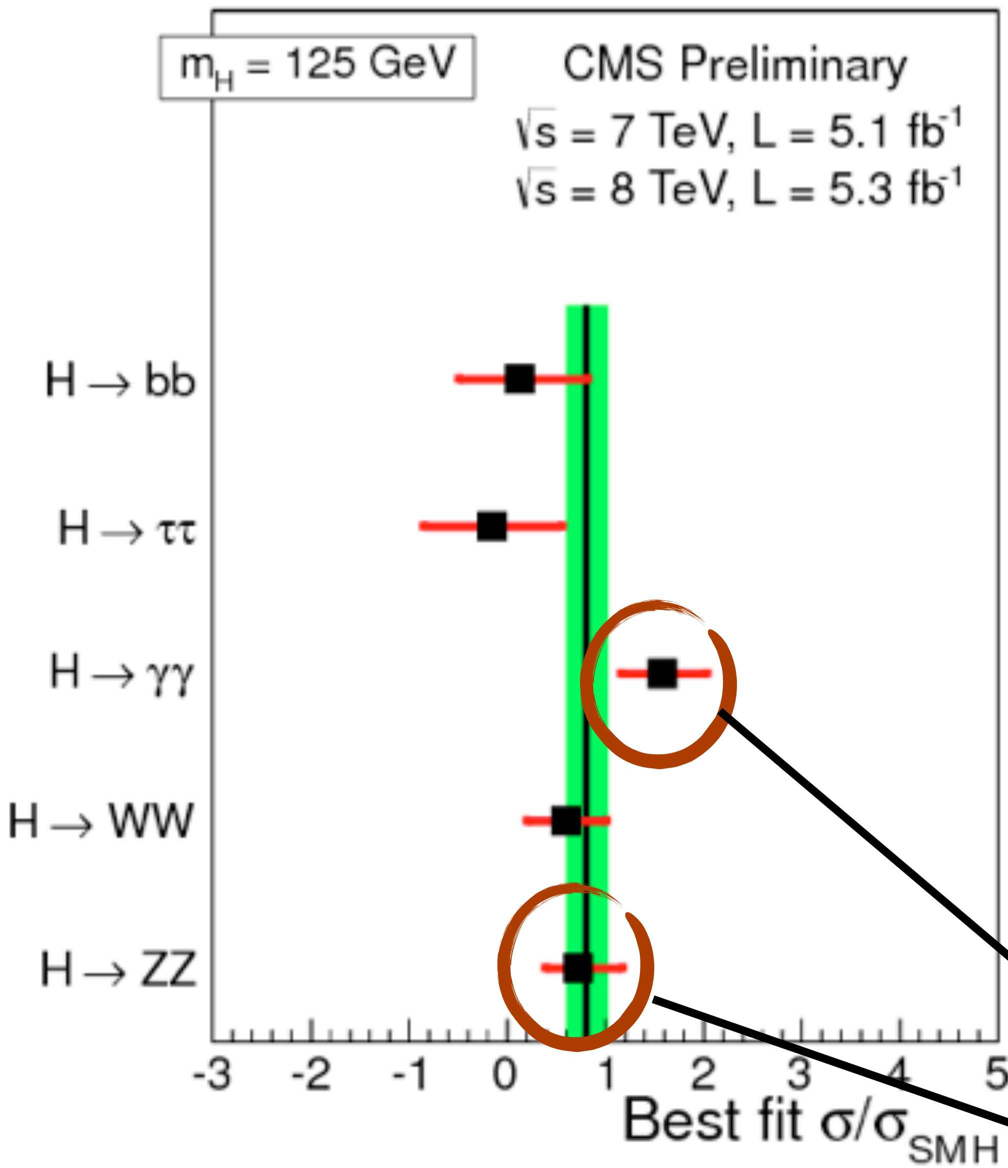


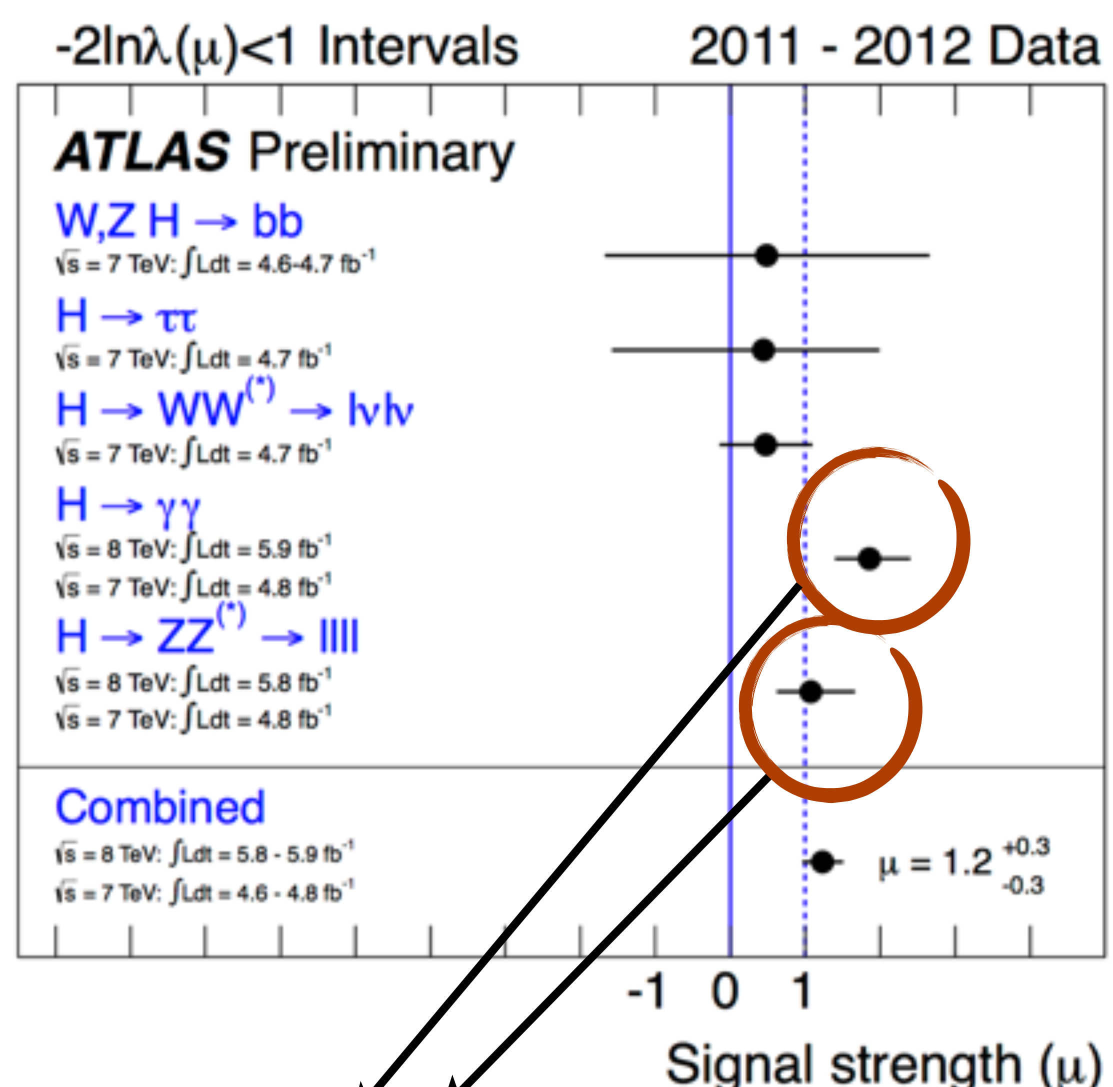


- CMS: 110-123 ... 127-600 GeV, excluded at 95% C.L.
- ATLAS: 110-123 ... 130-558 GeV, excluded at 95% C.L.
- Event excesses are observed where ~ 125-126 GeV, mainly contributed by di-photon and ZZ searches
- Under background-only hypothesis, => discovery of a new boson

Can The LHC Results Be Fit Well In Supersymmetry ?

[Atlas + CMS, 2012]





Key quantities for fit: (1) invariant mass mh ~ 125 GeV;
(2) signal rates of di-photon and ZZ

A little over interpreting ! But, it is fun to see what it might mean if this is true.

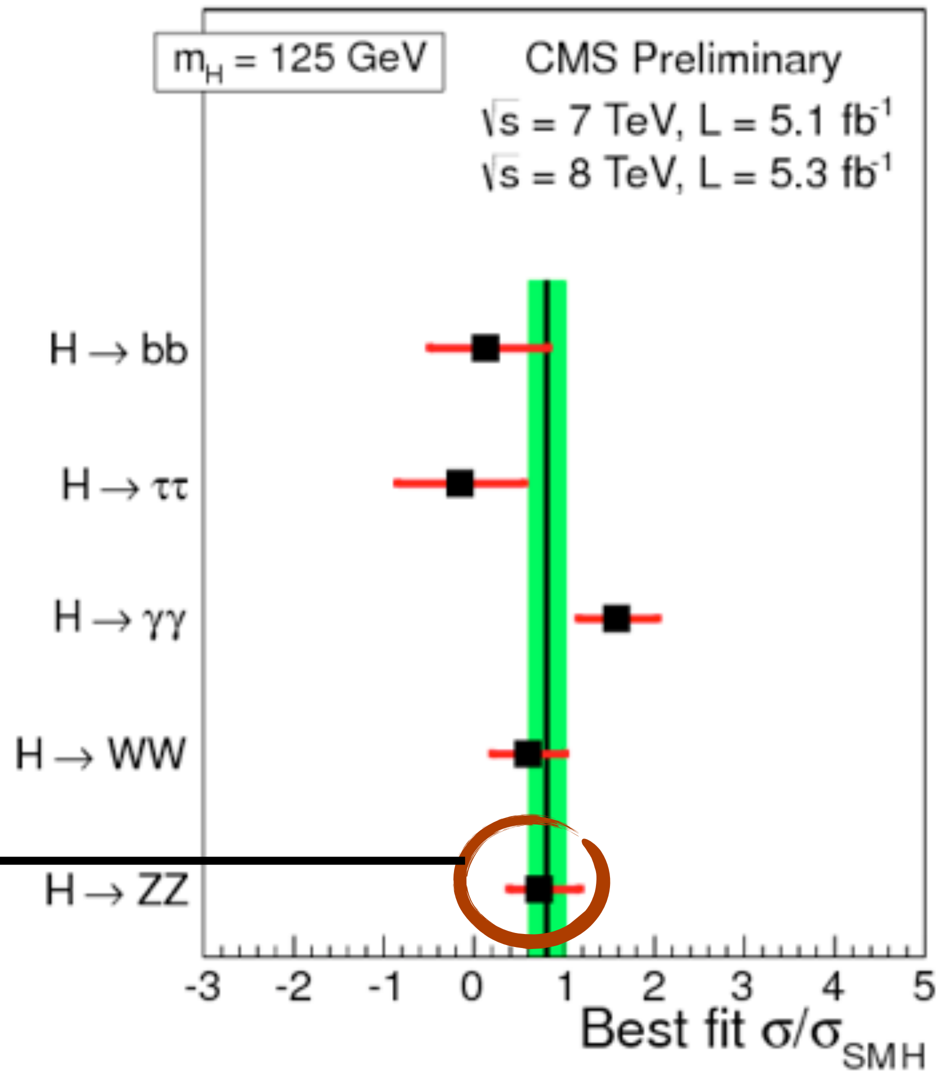
Suppressed $b\bar{b}$ Decay Width?

$$\sigma_{\gamma\gamma} = \sigma_{h_{SM}} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{b\bar{b}} + \sum_{SM}^{i\neq b\bar{b}} \Gamma_i}$$

- Obviously, the di-photon signal rate can be enhanced. (See Spencer's talk)
- In SUSY, this can be achieved by suppressing

$$\frac{y_{hb\bar{b}}}{y_{hb\bar{b}}^{SM}} = -\frac{\sin\alpha}{\cos\beta}$$

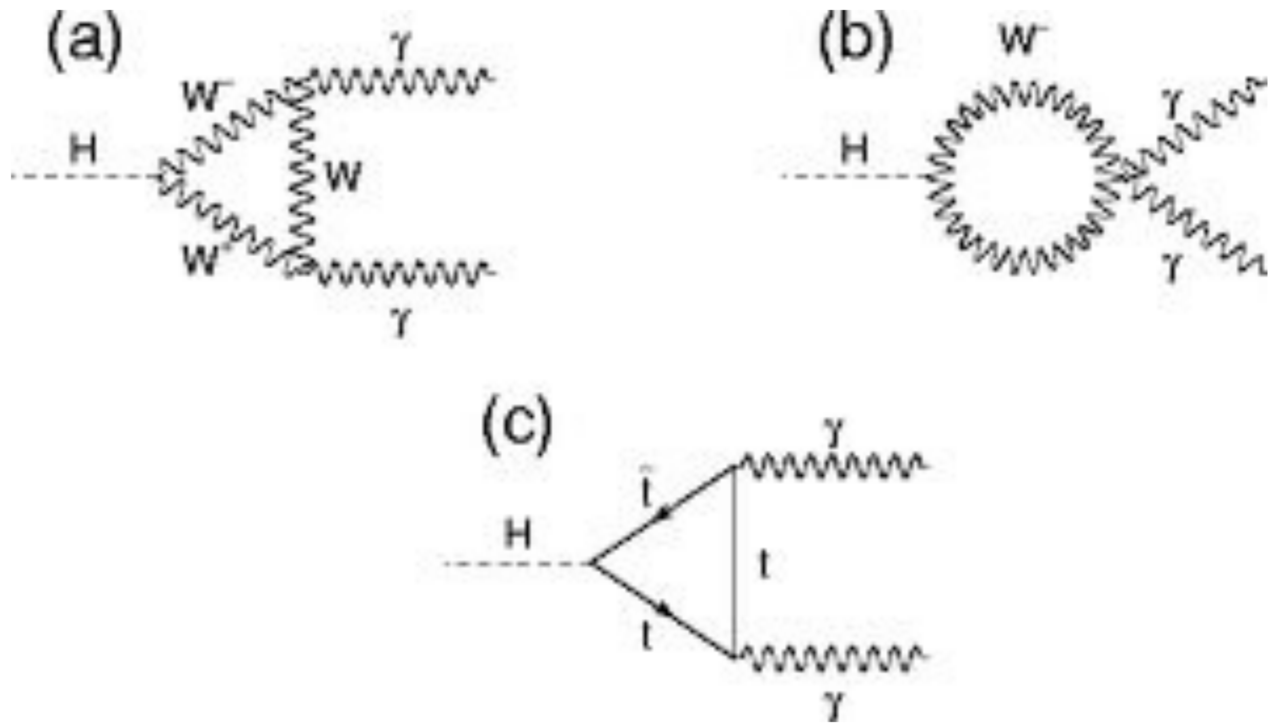
$$\begin{pmatrix} \mathrm{Re}(H_u) \\ \mathrm{Re}(H_d) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v_u + h\cos\alpha + H\sin\alpha \\ v_d - h\sin\alpha + H\cos\alpha \end{pmatrix}$$



But, the ZZ signal rate tends to be enhanced as well - seems not very consistent with the current observation at the LHC

Enhanced γγ Decay Width ?

$$\sigma_{\gamma\gamma} = \sigma_{h_{\rm SM}} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{b\bar{b}} + \sum_{\rm SM}^{i\neq b\bar{b}} \Gamma_i}$$



- Loop effect, mediated by charged particles
- Described by an effective theory

$$\mathcal{L}_{\rm eff} = \frac{-\alpha_{\rm EM} I}{2\pi} \frac{h_{\rm SM}}{v_{\rm EW}} F_{\mu\nu}F^{\mu\nu}$$

Effective Coupling

- Any particles coupled with the Higgs boson can get a mass from the Higgs VEV.

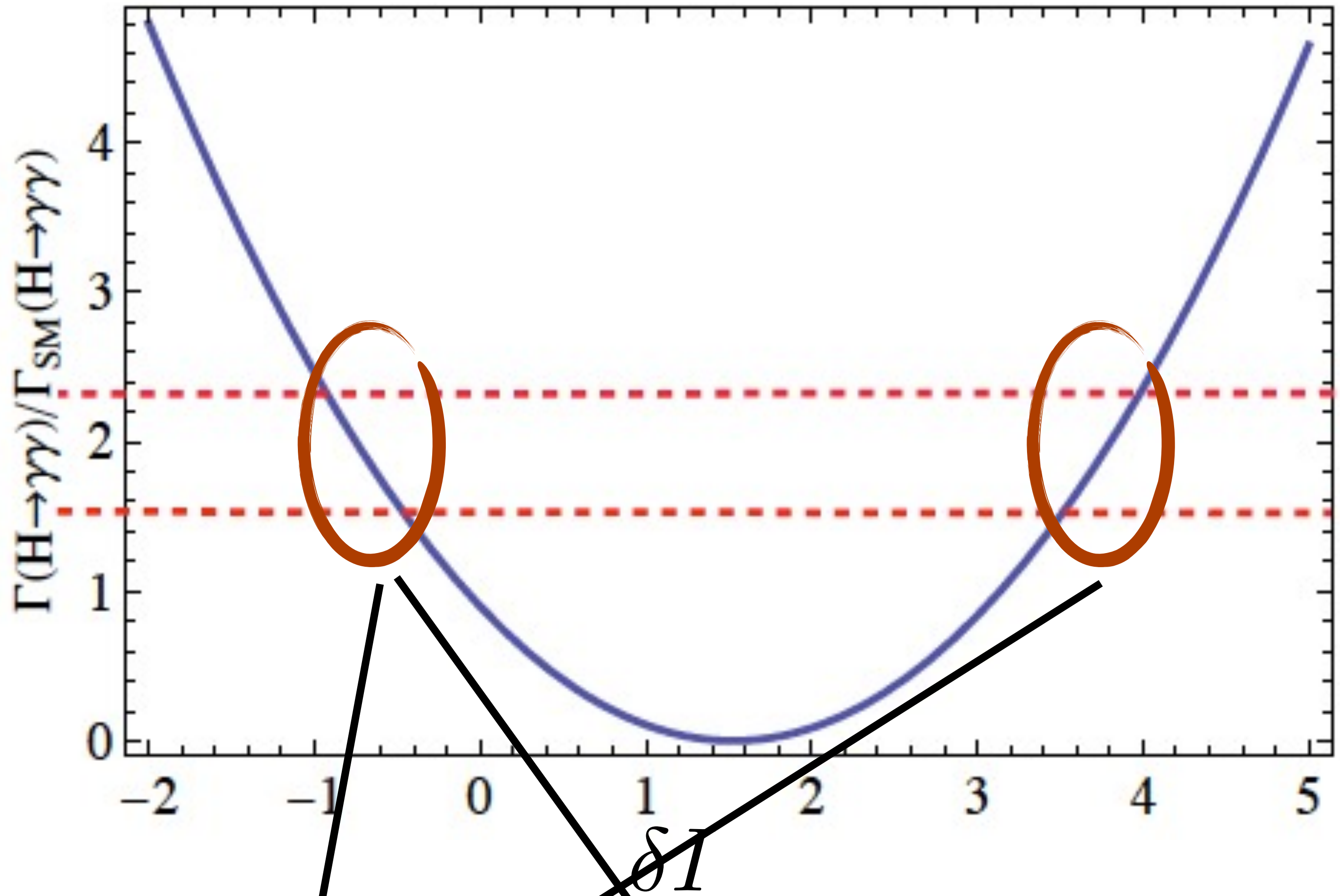
- I can be calculated through the photon self-energy corrections (e.g., M. Carena, et. al., 12')

$$I = \sum_k \frac{b_k}{4} \frac{\partial}{\partial \log v_{\mathrm{EW}}} \log\left(\det \mathcal{M}_k^2\right)$$

- SM - mainly controlled by the W and top-mediated loops: Iw ~ -2.1, It ~ 0.5
- Generalized to SUSY

$$I = \sum_k \frac{b_k}{4} \left[\cos\alpha \frac{\partial}{\partial v_u} \log\left(\det \mathcal{M}_k^2\right) - \sin\alpha \frac{\partial}{\partial v_d} \log\left(\det \mathcal{M}_i^2\right)\right]$$

Constructive Correction To Eff Coupling



There exist two solutions.

The more economical one is to get a negative δI, because Iw + It is negative and such a NP correction is constructive.

Still Not Very Easy - Charged Fermion

- Yukawa-type mass only doesn't help much, because the sign of δI is fixed to be positive (similar to the contribution by top quark)

$$\delta I \propto \frac{Y_{f_i}}{M_{f_i}} = \frac{1}{v_{\mathrm{EW}}}$$

- Extra mass sources are needed for the mediator. Consider a system, where the mediators also get mass from mixing

$$\mathcal{M}_f^\dagger \mathcal{M}_f = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^{*2} & m_{22}^2 \end{pmatrix}$$

$$\delta I \propto \frac{\alpha\, b_{1/2}}{16\pi \left(m_{11}^2 m_{22}^2 - |m_{12}^2|^2\right)} \left(m_{11}^2 \frac{\partial}{\partial v} m_{22}^2 + m_{22}^2 \frac{\partial}{\partial v} m_{11}^2 - \frac{\partial}{\partial v} |m_{12}^2|^2 \right)$$

- Economical choice: the off-diagonal ones contain Higgs VEV contributions while the diagonal ones are controlled by, e.g., vector-like or softly SUSY breaking corrections

Still Not Very Easy - Charged Fermion

- In supersymmetry, charginos provide such a possibility

$$M_{\chi^c}(h) = \begin{pmatrix} M_2 & gh_u \\ gh_d & \mu \end{pmatrix}$$

- But, the partial of the off-diagonal ones is controlled by the SU(2) gauge coupling, which turns out to be not large enough.

Still Not Very Easy - Charged Scalar

- Single mass source can work. The simplest case is probably $Y_s H^\dagger H S^\dagger S$ with Ys < 0, which gives negative correction.
- In SUSY, this type of interaction arises from the FF* coupling of sfermions which is positive.
- Consider a system, where the mediators also get mass from mixing

$$\mathcal{M}_S^2 = \begin{pmatrix} \tilde{m}_L(v)^2 & \frac{1}{\sqrt{2}} v X_S \\ \frac{1}{\sqrt{2}} v X_S & \tilde{m}_R(v)^2 \end{pmatrix}$$

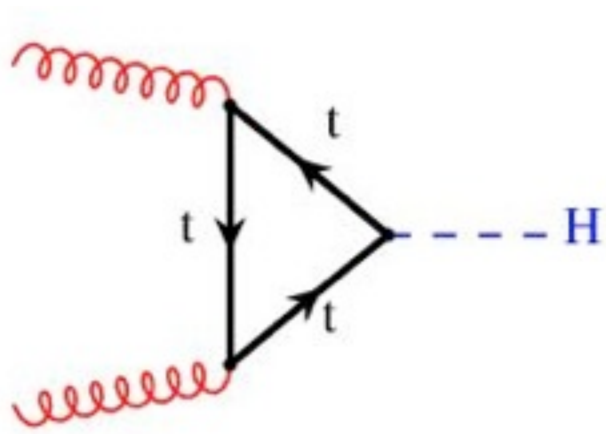
$$\frac{\partial \log(\det \mathcal{M}_S^2)}{\partial v} \simeq v \frac{(m_{L0}^2 + \frac{1}{2} c_L v^2) c_R + (m_{R0}^2 + \frac{1}{2} c_R v^2) c_L - X_S^2}{m_{S_1}^2 m_{S_2}^2}.$$

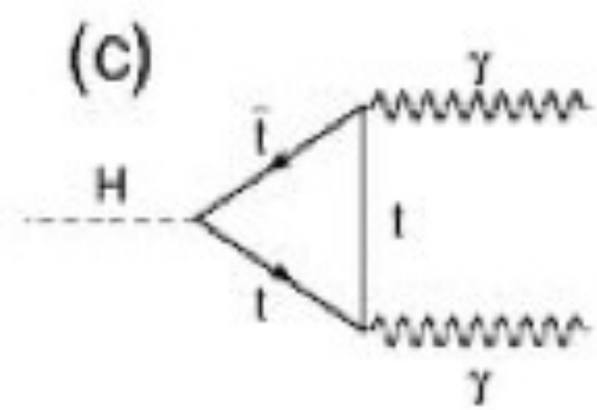
$$\tilde{m}_L^2 = \tilde{m}_{L0}^2 + \frac{1}{2} c_L v^2 , \qquad \tilde{m}_R^2 = \tilde{m}_{R0}^2 + \frac{1}{2} c_R v^2 ,$$

- Economical choice for SUSY: relatively large A-term + relatively light scalar

Still Not Very Easy - Charged Scalar

- In supersymmetry, stop quarks indeed can enhance the di-photon width in such a way, but not very helpful for the signal rate enhancement





- But, stau leptons do work, although marginal [Carena, et. al., 2011]

Why Extensions Of The MSSM ?

- What we learn from the SM: the Higgs mass is mainly controlled by the quartic coupling in the Higgs potential
- In the MSSM,
  - quartic terms arise from the SM D-terms

$$m_h^2 = m_Z^2 \cos^2 2\beta + \text{loop} \qquad \text{loop} \propto \log\left(\frac{M_{\text{SUSY}}}{M_{\text{top}}}\right)$$

  - mh = 125 GeV needs significant loop-level corrections, requiring

$$\Lambda_{\text{SUSY}} \gg m_{\text{top}}$$

- To lift the Higgs mass at tree-level, new quartic terms are needed

Extra U(1) Gauge Symmetry

- One possibility is from new non-decoupling D-term
- We will focus on gauged Peccei-Quinn symmetry:
  - Higgs fields are charged by definition. Bare mu term is forbidden
  - Provides a solution to the mu problem in the MSSM

$$\mathbf{W} \sim \lambda \mathbf{S}\mathbf{H_u}\mathbf{H_d}, \text{ with } \mu_{\text{eff}} = \lambda\langle S\rangle$$

- It is anomalous. Charged anomaly spectators are required
- Good! If some charged exotics happen to be light, they may help implement the mechanisms of the di-photon decay enhancement

Effective Theory

- $U(1)_{PQ}$ breaking can be quite involved. We focus on a simplified scenario.
  - PQ symmetry breaking scale f_{PQ} > $M_{Z'}$ > EW scale
  - Integrate out the radial modes. Keep saxion only
- SSB by **Si**, then we have

$$\mathbf{S_i} = f_i e^{q_i \mathbf{A}/f_{\rm PQ}} \qquad f_{\rm PQ} = \sqrt{\sum_i q_i^2 f_i^2}$$

$$\mathbf{A} = A + \sqrt{2}\theta\tilde{a} + \theta^2 F_A\,, \quad A = \frac{1}{\sqrt{2}}(s + ia)$$

$$\begin{aligned}
\mathbf{W_H} &= \lambda \mathbf{S H_u H_d} = \lambda f_S e^{q_S \mathbf{A}/f_{\rm PQ}} \mathbf{H_u H_d}\,, \\
\mathbf{K} &= \sum_i f_i^2 \exp\left(\frac{q_i(\mathbf{A}+\mathbf{A}^\dagger)}{f_{\rm PQ}} + 2 g_{\rm PQ} q_i \mathbf{V}_{\rm PQ}\right) \\
&\quad + \sum_a \mathbf{H}_a^\dagger \exp(2 g_{\rm PQ} q_a \mathbf{V}_{\rm PQ} + \mathbf{U}_{\rm SM}) \mathbf{H}_a,
\end{aligned}$$

Effective Theory

- Further integrating out the saxion in the PQ sector, we have

$$
\begin{aligned}
V_{\mathrm{WZ}} \;=\;& (|\mu_{\mathrm{eff}}|^2 + m_{H_u}^2)|H_u|^2 + (|\mu_{\mathrm{eff}}|^2 + m_{H_d}^2)|H_d|^2 \\
& -2B_\mu \mathrm{Re}(H_u H_d) + \frac{1}{8}(g_2^2 + g_Y^2)(|H_u|^2 - |H_d|^2)^2 \\
& -g_{\mathrm{PQ}} q_{H_u} \langle D_{\mathrm{PQ}} \rangle (|H_u|^2 + |H_d|^2) \\
& +a_1 |H_u H_d|^2 + a_2 (|H_u|^2 + |H_d|^2)^2 \\
& +a_3 \mathrm{Re}(H_u H_d)(|H_u|^2 + |H_d|^2) \,. \qquad (4)
\end{aligned}
$$

$$
a_1 \;=\; \mathcal{O}(\lambda^2) \,, \quad a_2 \;=\; \frac{1}{2}\, g_{\mathrm{PQ}}^2 q_{H_u}^2 \delta^2 + \mathcal{O}(\lambda^2) \,,
$$

$$
a_3 \;=\; \frac{-4A_\lambda \lambda g_{\mathrm{PQ}}^2 q_{H_u}^2 f_S}{m_s^2} + \mathcal{O}(\lambda^3) \,.
$$

$$
m_s^2 = 2 g_{\mathrm{PQ}}^2 f_{\mathrm{PQ}}^2 (1 + \delta^2) \text{ with } \delta^2 = \frac{\sum_i m_{S_i}^2 q_i^2 f_i^2}{g_{\mathrm{PQ}}^2 f_{\mathrm{PQ}}^4}
$$

- Non-trivial corrections to the MSSM potential due to the PQ D-term require sizable softly SUSY breaking effects in the PQ sector!

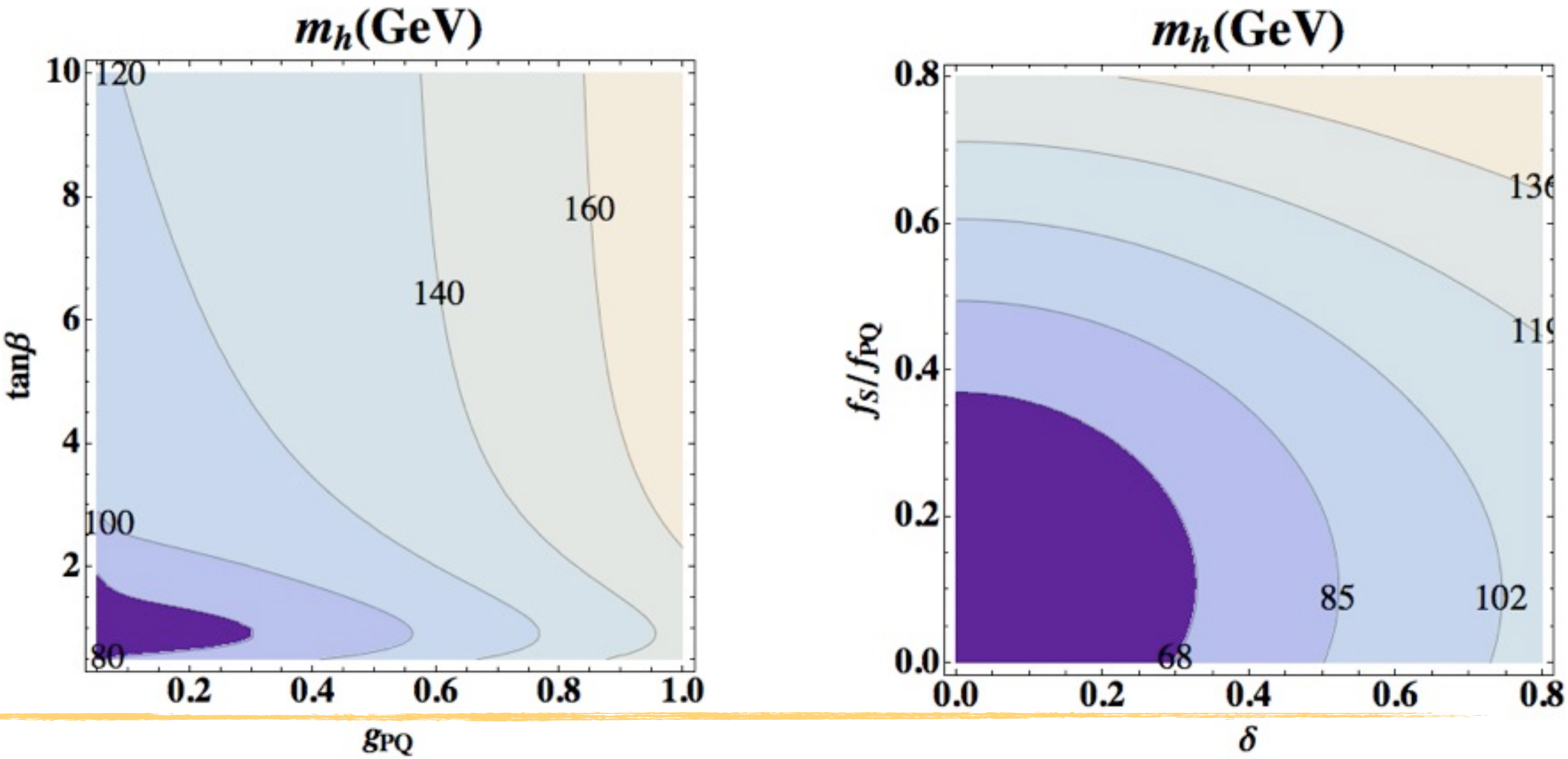
Gauged Peccei-Quinn Symmetry

$$(M_h^2)_{\text{tree}} \approx m_Z^2 \cos^2 2\beta + \left(\frac{a_1}{2}\sin^2 2\beta + 2a_2 + a_3 \sin 2\beta\right) v_{\text{EW}}^2$$

New contribution

Six free parameters at tree level :

$$g_{\text{PQ}}, f_{\text{PQ}}, \tan\beta, \frac{f_S}{f_{\text{PQ}}}, \lambda, \frac{A_\lambda}{f_{\text{PQ}}}$$



One Anomaly-free U(1)PQ Model

Vector-like mass terms for non-colored exotic charged fermions

$$
\begin{aligned}
\mathbf{W} \quad = \quad & \mathbf{W_I} + \beta^{pq}\mathbf{S D_p D^c_q} \\
& + \delta_N \mathbf{S_1 N N^c} + \delta_X \mathbf{S_1 X X^c} \\
& \boxed{+\gamma^p(\mathbf{H_u D_p X^c} + \mathbf{H_d D_p N^c}) \\ +\gamma^q_c(\mathbf{H_d D^c_q X} + \mathbf{H_u D^c_q N})} \\
& + \mathbf{W}_{\mathrm{Y}}(\mathbf{H_u} \leftrightarrow \mathbf{D_k}, \mathbf{H_d} \leftrightarrow \mathbf{D^c_k}) \\
& + \mathbf{W}_{\mathrm{LQ}} + \mathbf{W}_{\mathrm{S}}
\end{aligned}
$$

Indeed, there exist color-neutral superfields which can couple to Higgs fields

Particles	Gauge charges	Particles	Gauge charges
$\mathbf{L_i}$	(1; 2; −1/2; 1/2)	$\mathbf{Q_i}$	(3; 2; 1/6; 1/2)
$\mathbf{\bar{N}_i}$	(1; 1; 0; 1/2)	$\mathbf{\bar{u}_i}$	($\bar{3}$; 1; −2/3; 1/2)
$\mathbf{\bar{e}_i}$	(1; 1; 1; 1/2)	$\mathbf{\bar{d}_i}$	($\bar{3}$; 1; 1/3; 1/2)
$\mathbf{H_d}$	(1; 2; −1/2; −1)	$\mathbf{H_u}$	(1; 2; 1/2; −1)
$\mathbf{T_1}$	(3; 1; 2/3; −1)	$\mathbf{T^c_1}$	($\bar{3}$; 1; −2/3; −1)
$\mathbf{T_2}$	(3; 1; 2/3; −1)	$\mathbf{T^c_2}$	($\bar{3}$; 1; −2/3; −1)
$\mathbf{T_3}$	(3; 1; −1/3; −1)	$\mathbf{T^c_3}$	($\bar{3}$; 1; 1/3; −1)
$\mathbf{D_1}$	(1; 2; 1/2; −1)	$\mathbf{D^c_1}$	(1; 2; −1/2; −1)
$\mathbf{D_2}$	(1; 2; 1/2; −1)	$\mathbf{D^c_2}$	(1; 2; −1/2; −1)
$\mathbf{X}$	(1; 1; 1; 2)	$\mathbf{X^c}$	(1; 1; -1; 2)
$\mathbf{N}$	(1; 1; 0; 2)	$\mathbf{N^c}$	(1; 1; 0; 2)
$\mathbf{S}$	(1; 1; 0; 2)	$\mathbf{S^c}$	(1; 1; 0; −2)
$\mathbf{S_1}$	(1; 1; 0; −4)	$\mathbf{S^c_1}$	(1; 1; 0; 4)
$\mathbf{S_2}$	(1; 1; 0; −2)		

$$
\mathbf{W}_{\mathrm{LQ}} \quad = \quad \alpha^{pq}\mathbf{S T_p T^c_q} + \alpha^{33}\mathbf{S T_3 T^c_3} + \kappa^{rs}\mathbf{L_r Q_s T_3} + \kappa^{rsp}\mathbf{\bar{N}_r \bar{u}_s T_p}
$$

One Benchmark: Light Charged Exotic Fermion

g_{PQ}	f_{PQ} (GeV)	f_S/f_{PQ}	A_λ/f_{PQ}	λ
0.6	2500	0.4	0.1	0.3
$\tan\beta$	δ	A_γ (GeV)	A_{γ_c} (GeV)	γ, γ_c
1.3	0.6	0	0	1.6
m_D (GeV)	m_X (GeV)	$m^2_{\tilde{D},\tilde{X},\tilde{N}}$ (GeV^2)	$A_{\tilde{t}}$ (GeV)	$m^2_{\tilde{Q}_3}, m^2_{\tilde{t}}$ (GeV^2)
440	330	1000^2	1200	500^2
a_1	a_2	a_3	B_μ (GeV^2)	$\mu_{\rm eff}$ (GeV)
0.06	0.9	-0.02	7.5×10^4	300
m_h (GeV)	$m_{\psi 1^c}$ (GeV)	$m_{\psi 1^0}$ (GeV)	$m_{\phi 1^c}$ (GeV)	$m_{\phi 1^0}$ (GeV)
125	105	105	943	943
$R(h \to \gamma\gamma)$	ΔS	ΔT		
1.8	0.11	0.10		

Enhanced di-photon signal rate!

Relatively small DeltaT, because we work in the region with approximate custodial symmetry

Unlike charginos in the MSSM, the coupling between h and the charged light exotic fermion is controlled by Yukawa couplings

One Benchmark: Light Charged Exotic Scalar

g_{PQ}	f_{PQ} (GeV)	f_S/f_{PQ}	A_λ/f_{PQ}	λ
0.6	2500	0.4	0.1	0.3
$\tan\beta$	δ	A_γ (GeV)	A_{γ_c} (GeV)	γ, γ_c
6	0.6	1440	1000	0.5
m_D (GeV)	m_X (GeV)	$m^2_{\tilde{\bar{D}},\tilde{\bar{X}},\tilde{N}}$ (GeV^2)	$A_{\tilde t}$ (GeV)	$m^2_{\tilde Q_3}, m^2_{\tilde t}$ (GeV^2)
500	350	100^2	1200	500^2
a_1	a_2	a_3	B_μ (GeV^2)	$\mu_{\rm eff}$ (GeV)
0.06	0.07	-0.02	7.5×10^4	300
m_h (GeV)	$m_{\psi 1^c}$ (GeV)	$m_{\psi 1^0}$ (GeV)	$m_{\phi 1^c}$ (GeV)	$m_{\phi 1^0}$ (GeV)
125	325	325	104	233
$R(h \to \gamma\gamma)$	ΔS	ΔT		
1.7	0.03	0.08		

Enhanced di-photon signal rate!

Leading to a large coupling between h and the charged light exotic Scalar! Recall - it is controlled by

$\mathbf{H_u D_p X^c}$

Conclusions

- The two benchmarks are presented in a specific model, but they represent large classes of models in which an enhancement of the $h \to \gamma\gamma$ signal rate does not lead to a violation of the EWPT constraints.
- Benchmark I: light charged fermion + large coupling with Higgs field + approximate custodial symmetry
- Benchmark II: light charged scalar + relatively large A-parameter
- If only the $h \to \gamma\gamma$ signal rate is enhanced while the other ones are not modified, it is very likely that the new exotics carry the EW charges only
- The collider signals of their directly search are similar to the EW-ino and the slepton ones


Thank you!